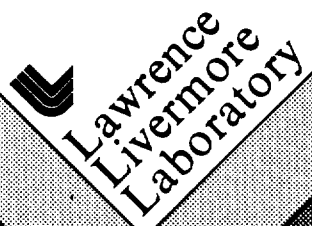# THE TANDEM MIRROR REACTOR AS A SYNTHETIC FUEL PRODUCER

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DISCLAIMER

The Tandem Mirror Reactor as a Synthetic Fuel Producer*

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Introduction

We believe that fusion should and must play as strong a role in the production of fuels and chemical feedstocks as it is expected to play in the production of electricity. The role, in fact, may be even stronger since the production of fuel in the form of hydrogen, hydrocarbons, and their derivatives useful for transportation, industrial processes, or for residential and commercial use or the production of chemicals based on hydrogen or hydrocarbons is three times as high in the United States as is the use of energy for the production of electricity.

We further believe that fuel production is not inimical to electricity production from fusion but is complementary to it and strengthens the base of the entire fusion program.

We report on a scoping design of a fusion reactor based on tandem mirror physics coupled to thermochemical processes for the production of hydrogen.

Flow of Energy in the U.S.

The reason for coupling synfuels to fusion, in terms of a U.S. energy problem, is that the principal shortfall in the future United States energy flow will continue to be in liquid and gaseous fuels as it currently is and not in electrical power. In the time period for fusion's emergence, it is likely that the demand for electrical energy will be outweighed by the demand for energy in the form of portable fuels by a ratio of three to one. Incorporating synthetic fuel production in the fusion program both broadens the fusion program's base and is responsive to a national need.

Figure 1 illustrates the U.S. energy flow picture for 1979. The future overall demand would be expected to increase by perhaps 5% per year on the average if the past is any guide.

U.S. ENERGY FLOW – 1979
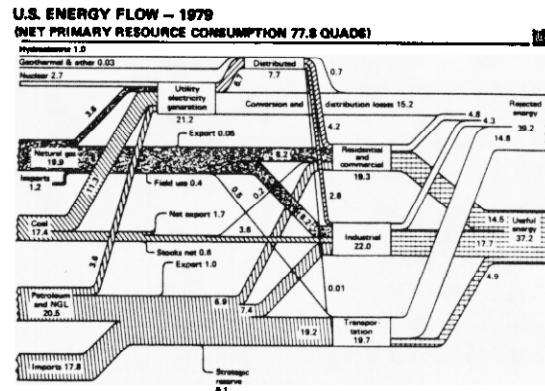(NET PRIMARY RESOURCE CONSUMPTION 77.8 QUADS)

Figure 1

The division of energy flow should not be expected to change materially.

Even though our fusion reactor may be 20 or 30 years away from commercial fruition, now is an appropriate time to begin to plan and study the fusion/synfuel tie. An interesting way to begin is with the tandem mirror reactor (TMR) which, as we shall see, has some distinct advantages over other energy producers for this application.

The Technical Choice of the TMR

The fusion reactor as an energy source was critical to our study, and we investigated how well fusion might produce synthetic fuels, as well as what influence the fuel production would have on basic reactor design.

It can be stated that the main influence synfuel production had on reactor design had to do with blanket modules, those units surrounding the plasma that convert the neutrons' kinetic energy to thermal energy and in the case of the D-T cycle also produce the tritium part of the fueling needs by neutron-lithium reactions. Other engineering elements of the reactor remain substantially the same. The physics may be slightly easier due to the basic size of a fusion reactor for synfuels compared to one for electrical production. The synfuel plant is larger by perhaps a factor of two and thus the

reactor Q can become higher.

TMR Design Parameters – Thermochemical Hydrogen vs. Electrical Production

Table 1 provides a comparison between a conceptual reactor design for fuel production and one for electrical production.

TABLE 1

Example Design Parameters for the Tandem Mirror Reactor For Synfuel Production or Electrical Production

		Synfuel	Elec.
Fusion Power	(MW_f)	5680	3500
Thermal Power	(MW_{th})	4945	3360
First Wall Loading	(MW_{th}/m^2)	2.0	2.6
ECH Power Delivered	(MW)	330	260
Neutral Beam Power Delivered			
Central Cell	(MW)	0.0	0
Barrier Cell	(MW)	85	58
Plug	(MW)	8.5	48
Central Cell Length	(m)	260	125
Central Cell First Wall Radius	(m)	1.4	1.7
Global Reactor Q-Value		13.3	9.6
P_{net}	(MWe)	0	1000
A_c			
B_c	(T)	~2	~2
B_p	(T)	~12	~12

Assembly, Disassembly and Accessibility

A primary technical reason for choosing the tandem mirror was its highly favorable reactor configuration. The configuration not only allows the design of relatively simple blanket modules that are the principal source of the process heat but puts them together into a workable package.

The sequence of figures that follow, Figs. 2A, B, C, D, E, F, G; illustrates how the blanket modules, tailored for synfuel, thermochemical cycle use may be assembled into a highly manageable, serviceable, accessible reactor for producing energy.

The Operating Principle of the Cauldron Blanket Module

A cross-sectional view of the cauldron module is illustrated in Figure 3. Notice the module's resemblance to a pool boiler. It is, however, substantially more complicated than a pool boiler due to geometric effects, due to the exponential energy generation in the fluid contained within the module and, last but not least, due to MHD effects on the convective mixing of the two liquid metals, lithium and

sodium, we have chosen to use in the pool. The two liquids in this cauldron module act as both the neutron moderator and heat transfer fluid, absorbing energy in direct proportion to the energy input and transferring it by latent heat of vaporization of the sodium to a heat exchanger in the dome of the vessel. The
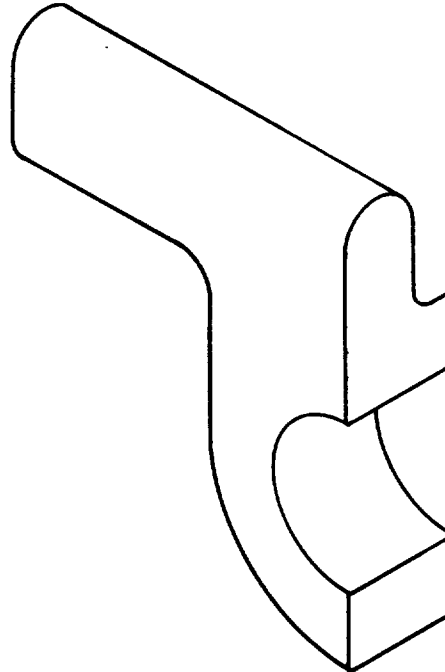
Figure 2A A single cauldron blanket module
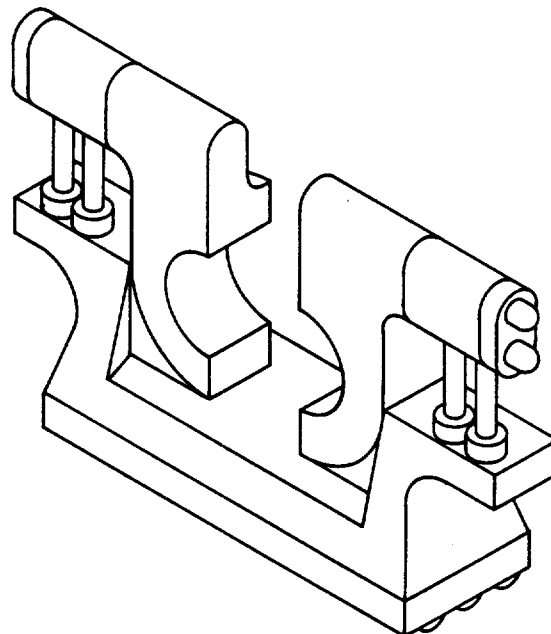
Figure 2B A retracted pair of cauldron modules or an assembly
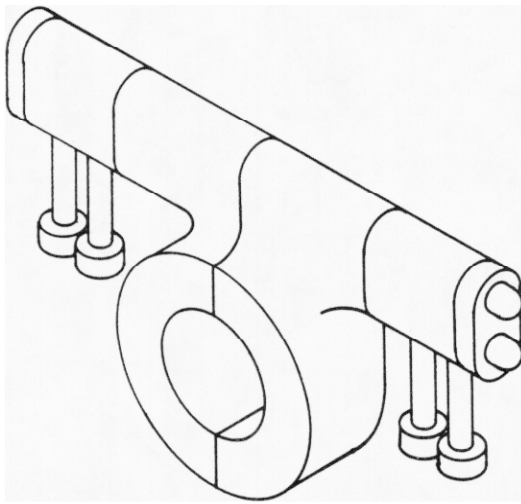
Figure 2C Two modules ready for assembly with
a central cell solenoid
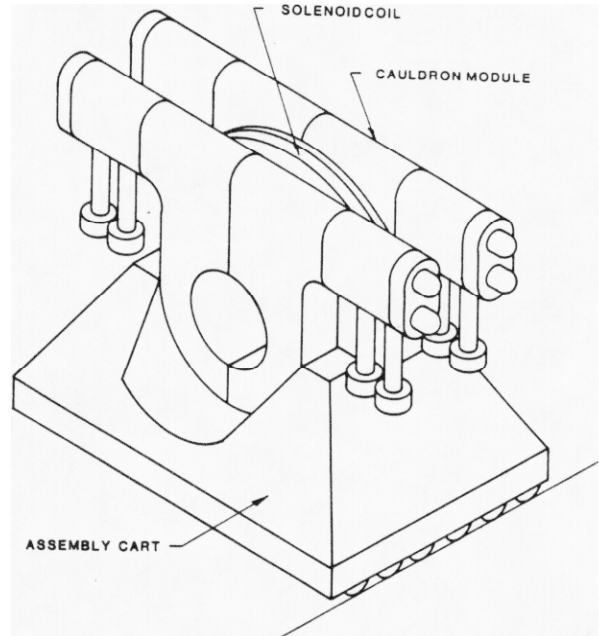
Figure 2D A unit cell or its assembly cart

CROSS SECTION THRU 2 UNIT CELLS

Figure 2E

UNIT CELL

INJECTORS

END PLUG

TO DIRECT CONVERTER
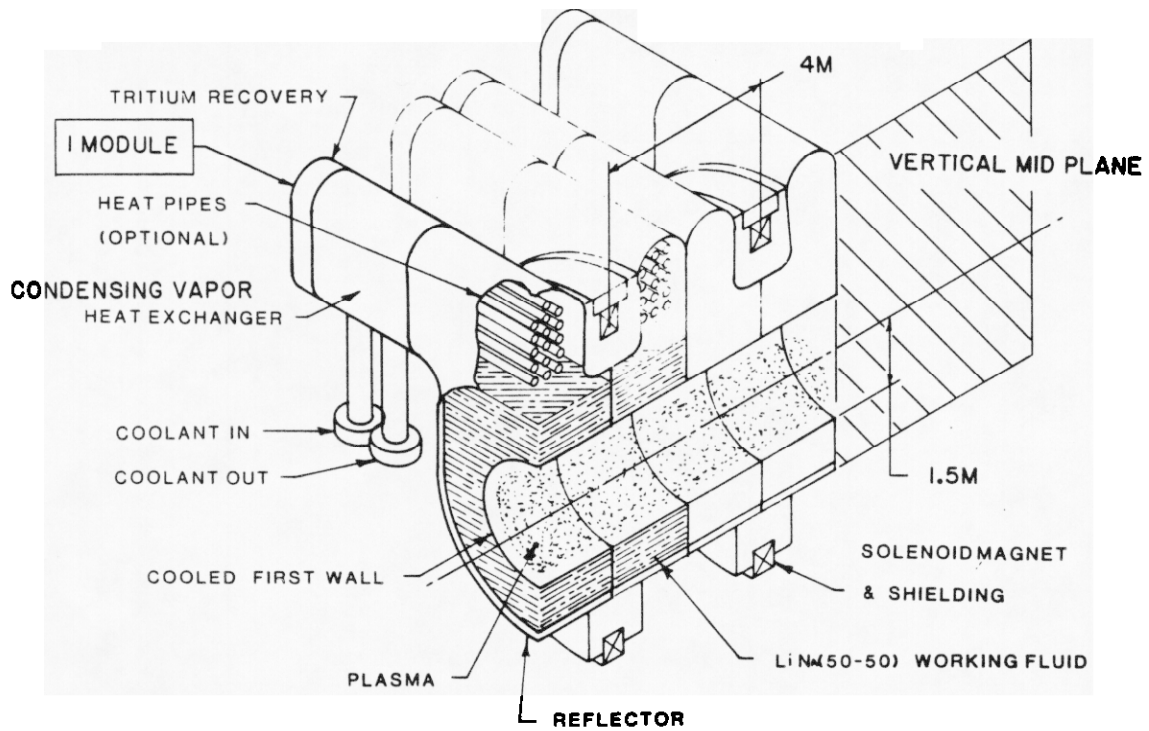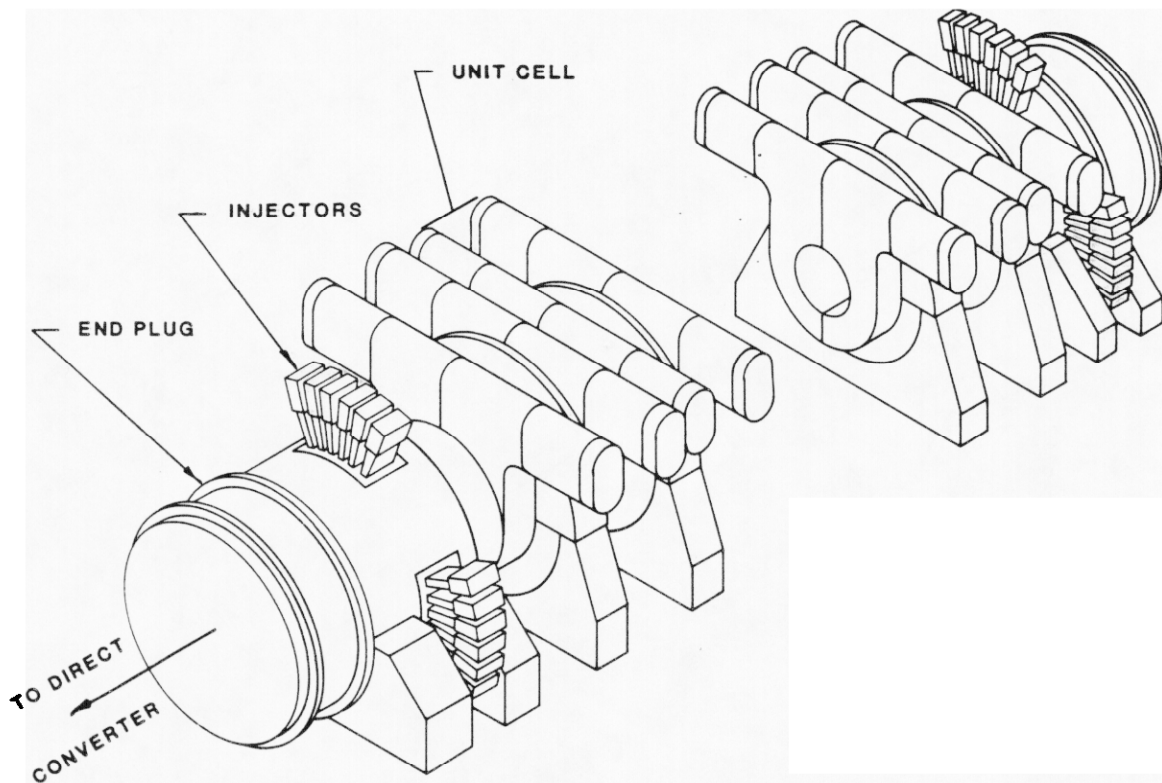
Figure 2F Unit cells installed in reactor

A UNIT CELL

SUPER COND. COIL

CAULDRON MODULE

COOLANT SUPPLY AND RETURN HEADERS
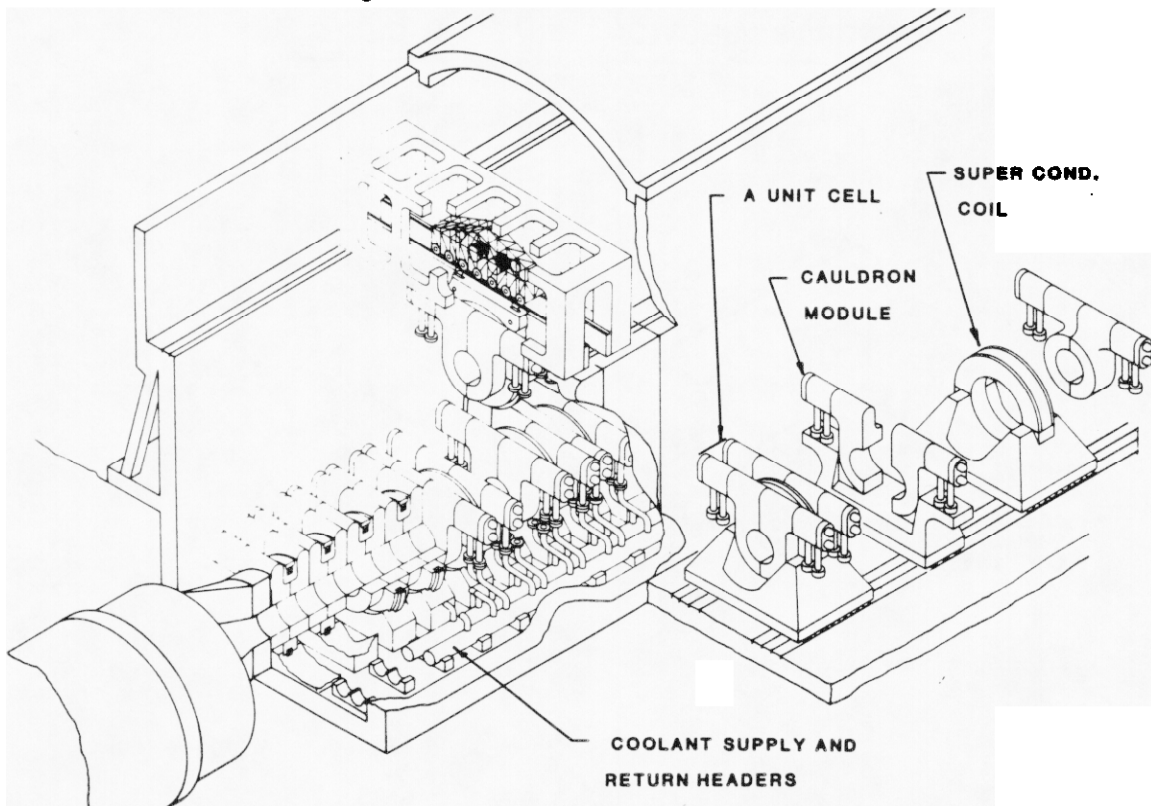
Figure 2G A part of the main reactor showing states of assembly or disassembly

4

Deuterium + Tritium	Energetic Neutron + charged particle

The first energy form, the kinetic energy of the neutron, is captured in the moderating blanket surrounding the reacting plasma and thermal energy is produced. The cylindrical plasma is physically located in the TMR's central cell in a zone that is about 200 meters long for the synfuel production application. The plasma is contained within the central cell by the retarding action of the mirror end cells whose electrostatic potential causes the deuterium and tritium ions to be reflected back and forth sufficiently long so that some of them react with one another and fuse. Figure 4 illustrates this potential and the magnetic fields associated with the tandem.
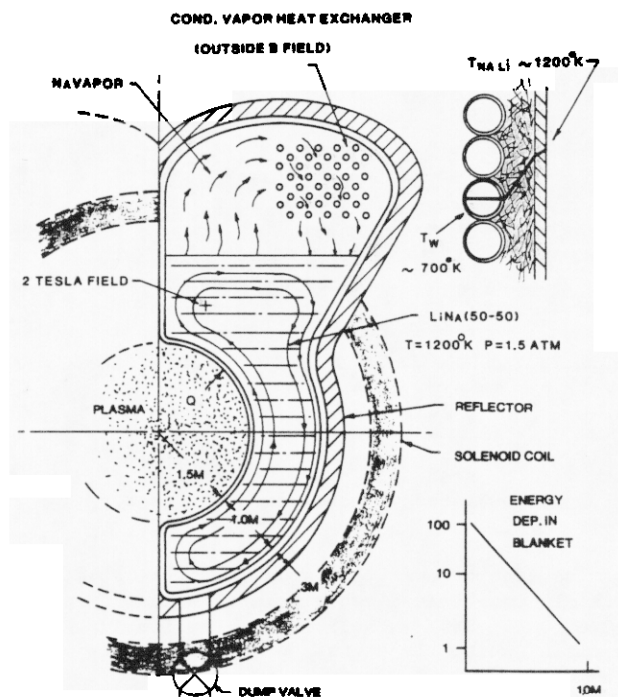
Figure 3

lithium performs the function of tritium breeding. In the dome the condensing vapor heat exchanger (CVHX) transfers the thermal energy out of the module to various chemical processors located some distance from the reactor.

The sodium preferentially vaporizes, leaving behind the lithium in the liquid state to do its neutron moderating, tritium-producing function. The sodium vapor, traveling at vapor velocities roughly 8-10 m/s at 1200 K, condenses on the heat exchanger tubes in the dome, yields energy and returns as liquid droplets to the pool, thus completing the cycle. We have selected the LiNa mixture for our studies but also considered potassium. The two fluids are miscible and tritium production with a 50-50 mix is greater than 1. The neutronics of the potassium is a little less favorable although the LiK can run cooler for the same vapor velocity. LiRb or LiCs are other mixes or compounds that may be of interest.

The Tandem Mirror Reactor and Its Energy Sources

The tandem (TMR) is a steady state, driven, fusion device. It operates on the deuterium-tritium cycle. Energy from the reactor is produced in two primary forms as evidenced by equation 1.

Figure 4

The second energy form is that contained in the charged alpha particle. On forming, the alpha begins to lose some of its 3.5 Mev energy by heating the plasma through a series of collisions with electrons and ions and finally, at some degraded energy, leaves the system (the central cell) through the ends as do the deuterium and tritium ions that did not react. All the alpha particle energy may now be accounted for as the sum of its residual energy plus the enhanced energy of the exiting ions. This energy is recovered in a direct convertor located beyond the end cells. The direct convertor produces two forms of energy, an electrical dc component which we use in our point design to drive the reactor, and a thermal component which, for our thermochemical cycle, furnishes energy for process chemistry. The neutrons, as they are moderated in the blanket, produce some additional energy by exothermic

neutron-lithium reactions.

Partitioning the Energy for Process Chemistry

At the blanket region it is convenient for structural and thermodynamic reasons to divide all of the blanket energy into two sources of supply usable for the process chemistry. The first supply source is the cooled first wall zone, characterized by modest (700 K) energy levels since the first wall serves as the struct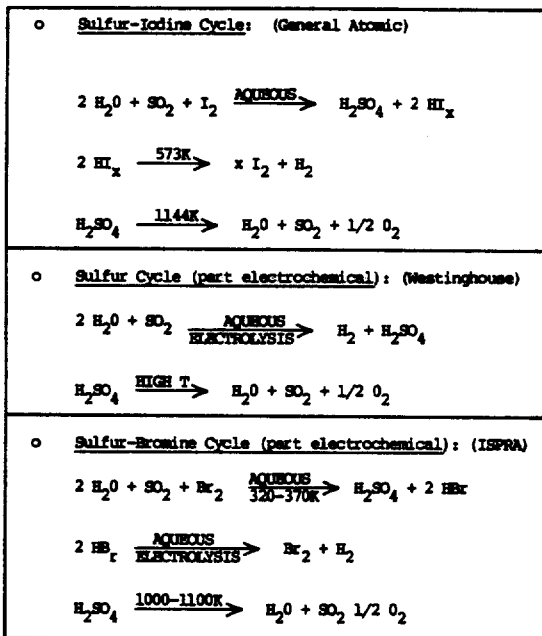ural container for the fluid in the module. The second zone is where high temperature, high-quality heat (1200 K) is produced for the main part of the thermochemical processes.

The Thermochemical Cycles

The TMR is used as an energy source to produce fuel (H_2) via three candidate thermochemical cycles.

```
o   Sulfur-Iodine Cycle:  (General Atomic)

                  AQUEOUS
    2 H₂O + SO₂ + I₂  ─────────>  H₂SO₄ + 2 HI_x

              573K
    2 HI_x  ─────────>  x I₂ + H₂

              1144K
    H₂SO₄  ─────────>  H₂O + SO₂ + 1/2 O₂


o   Sulfur Cycle (part electrochemical):  (Westinghouse)

                  AQUEOUS
    2 H₂O + SO₂  ─────────────>  H₂ + H₂SO₄
                 ELECTROLYSIS

              HIGH T
    H₂SO₄  ─────────>  H₂O + SO₂ + 1/2 O₂


o   Sulfur-Bromine Cycle (part electrochemical):  (ISPRA)

                  AQUEOUS
    2 H₂O + SO₂ + Br₂  ─────────>  H₂SO₄ + 2 HBr
                       320-370K

                  AQUEOUS
    2 HBr  ─────────────>  Br₂ + H₂
           ELECTROLYSIS

              1000-1100K
    H₂SO₄  ─────────────>  H₂O + SO₂ 1/2 O₂
```

These three cycles have been demonstrated on a laboratory scale.

The requirements for energy, thermal and electrical, for these three cycles are illustrated in table 2.

The Reactor Energy Balance, Thermal and Electric

For the thermochemical cycles, as Table 2 suggests, we are interested in limited electrical power production but primarily in the production of process heat and in the use of the available thermal energy out of the fusion reactor. Two regions of the tandem mirror fusion reactor provide this process heat: (1) the blanket and (2) the direct convertor. We will also use any surplus electrical energy out of the direct convertor over and above that

TABLE 2

Electrical and Thermal Requirements for Various Cycles Based on HTGR Heat Sources

Thermo-chemical Cycle	Thermal Eff.	Process Heat		Thermal energy used to generate electricity or shaft work	
		High Temp	Intermed. Temp	Electrolytic Demand	Process Shaft Work
General Atomic Sulfur Iodine	47%	24% 1250 K	51% 843 K	0	25%
Westinghouse Sulfur cycle	47%	23% 1200 K	20% 1100 K	57%	0
ISPRA Mark-13	46%	27% 1083 K	52% below 773 K	21%	0

which will be needed to satisfy circulating (driving) power requirements for the reactor itself.

The reactor energy balance, as it relates to the thermochemical cycles, is illustrated in Figure 5. We have established the following quantities which may be used with this energy balance.

AM	=	The blanket thermal energy.	(1)
$B(1-\eta_{dc})$	=	The direct convertor thermal energy.	(2)
$B\eta_{dc}$	=	The direct convertor electrical energy.	(3)
C	=	Thermal energy contribution from injected neutrals.	(4)

where, for the D-T cycle:

A	=	$0.8\ P_{inj}\eta_A\hat{Q}$ (The neutron energy fraction)	(5)
B	=	$0.2\ P_{inj}\eta_A\hat{Q} + P_{inj}\eta_A$ (The alpha or charged particle fraction)	(6)
C	=	$P_{inj}\ (1 - \eta_A)$ (The fraction of injected neutrals that don't get ionized)	(7)

The definitions of terms needed for Figure 5 are:

η_A	=	ionization efficiency.
M	=	blanket energy multiplication (from exothermic reactions).
η_{inj}	=	injector efficiency.
η_{dc}	=	direct convertor efficiency (converting charged particle kinetic energy to electrical).
η_{TH1}	=	thermal convertor efficiency (converting thermal energy to electrical.
η_{TH2}	=	thermal convertor efficiency.
P_{aux}	=	power required for pumps, refrigeration, and other fusion plant needs
$\hat{Q}$	=	fusion power produced/power injected

6

POWER BALANCE-MIRROR REACTOR WITH DIRECT CONVERSION PROCESS HEAT PRODUCTION FOR SYNFUELS
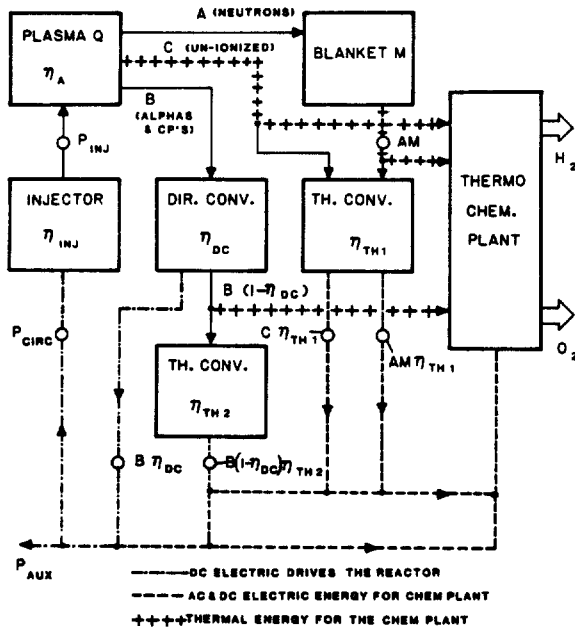

Figure 5

The value of P_{aux} is taken as a fraction, f, of the thermal and dc energy before conversion

$$P_{aux} = f (B + AM + C) \qquad (8)$$

By definition

$$P_{circ} = P_{inj}/\eta_{inj} \qquad (9)$$

The Uniqueness of the TMR

There is a uniqueness associated with the tandem mirror reactor open-ended physics geometry that increases the usefulness of this energy source over other contemporary energy producers such as solar energy concentrators, tokamaks, and high temperature gas cooled fission reactors (HTGR) for the production of synthetic fuels. This uniqueness may be noted in the energy balance figure and has to do with the fact that in the TMR open-ended mirror geometry there is a direct convertor which produces dc power that may be used in thermochemical cycles that have an electrical demand and/or an electrochemical step. The result of using the direct convertor is an improvement in overall efficiency as schematically illustrated in Figs. 6A and 6B.

The Influence of Q on the TMR's Uniqueness

To fully recognize the TMR as a unique energy source for synfuel (H₂) production, it will be stipulated that the dc electrical energy

The HTGR, the tokamak, solar energy concentrators must convert thermal energy to electrical energy at an efficiency η_{th} to drive the electrolysis step or meet other electrical demands of the thermochemical cycle.

Figure 6A HTGR, Tokamak or solar energy concentrator energy sources
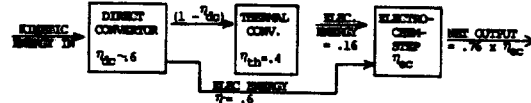
The tandem mirror reactor can drive the electrolysis step directly or provide other electrical demands directly using the reactor's dc electrical output.

Figure 6B The tandem mirror reactor energy source

component $B\eta_{dc}$ of the direct convertor will be used, in the first place, to satisfy the circulating power and the auxiliary needs of the reactor itself. This means simply that the dc component of the direct convertor drives the reactor and the ancillary equipment. No other energy input is required. There will be a specific value of $\hat{Q}$ at which this demand is exactly satisfied. For higher $\hat{Q}$ values, there will then be a surplus of dc electrical energy that will then be used by the thermochemical plant. No electrical energy is sold. For lesser values of $\hat{Q}$, some thermal energy from the reactor blanket or from the thermal part of the direct convertor would have to be converted to electrical energy to help drive the reactor. Figure 7 is a plot of how this electrical surplus
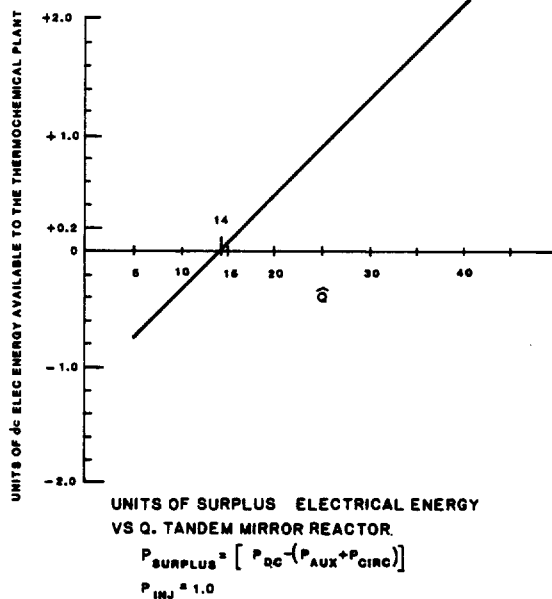

UNITS OF SURPLUS ELECTRICAL ENERGY
VS Q. TANDEM MIRROR REACTOR.

$$P_{SURPLUS} = \left[P_{DC} - (P_{AUX} + P_{CIRC}) \right]$$

$$P_{INJ} = 1.0$$

Figure 7

or deficiency, $P_{dc}-(P_{aux} + P_{circ})$, varies
as a function of Q. The representative set of
data for this plot are given in Table 3:

TABLE 3

Representative Quantities for the Energy Balance

P_{inj}	injection power	= 1.0 Unit
η_a	ionization efficiency	= 0.95
M	blanket energy multiplication	1.20
η_{TH}	thermal efficiency	= 0.40
η_{inj}	injector efficiency	= 0.60
f	fraction of thermal and dc energy before conversion	= 0.02
η_{dc}	direct convertor efficiency	= 0.55

It may be seen from Figure 7 that when the Q
value is about 14 or higher, there begins to be
a dc electrical component left over from the
reactor that can be used to drive such things as
electrolysis cells, pumps, motors, etc., in the
synfuel plant.

Relative to the total energy that the
reactor has created for synfuel purposes, the
fraction that is dc tends to a limit R, where R
is defined as surplus dc expressed in units of
equivalent thermal energy divided by the total
energy available to the process chemistry in
thermal units. Expressing surplus dc in thermal
units is somewhat of an artifice but is useful
in illustrating limits. This limit is indicated
in Figure 8 where we see that as Q gets larger
and larger, the dc percentage of the reactor's
output available for process chemistry tends to
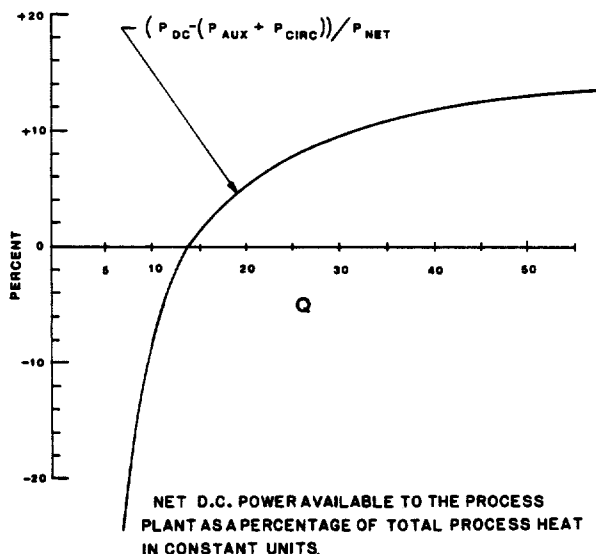a limit of about 13%.

NET D.C. POWER AVAILABLE TO THE PROCESS
PLANT AS A PERCENTAGE OF TOTAL PROCESS HEAT
IN CONSTANT UNITS.

Figure 8

Comments on the Tandem as an Energy Source

From Figures 7 and 8 some conclusions can be
reached.

1) At a Q value ~14 the TMR dc electrical
output is just large enough to feedback
and drive the reactor, leaving the
thermal fraction of the direct convertor
and the blanket thermal energy available
for process chemistry.

2) As Q values exceed 14 there is some
surplus dc electrical power available
for process chemistry.

3) As Q increases the direct current
electrical energy that is available for
process chemistry tends to a limit of
about 13% of the plant useful output.

4) The availability of this direct current
electrical energy from the TMR is an
asset that other energy producing
machines do not have. The HTGR, the
tokamak, the LWR, the FBR -- all of
these machines must go through the
thermal conversion step to produce this
electricity at a penalty that is
directly proportional to the thermal
efficiency. The tandem begins to avoids
the thermal step when values of Q exceed
14.

Looking to the Future - The TMR and the DD or D-He₃ Cycle

When we consider only the D-T fuel cycle,
there is a limit for the charged particle energy
out of the TMR that cannot exceed 20% of the
total energy output i.e., 3.5 Mev alphas (14.1
Mev neutrons + 3.5 Mev alphas).

If a D-D fuel cycle were to be considered
the picture changes significantly. With the D-D
cycle it is possible to have approximately 50%
of the raw energy output of the TMR in charged
particle form and convertible to electricity
directly. It is interesting to compare the two
cycles (the DT and the DD) for their overall
plant efficiency potential and also to compare
the TMR with the tokamak, the HTGR or a solar
concentrator under these circumstances. This
comparison is shown below in Fig. 9.

Planning Ahead

We have included comments on the tandem D-D
fuel cycle as a closure to this paper. We are
of the opinion that the D-D cycle, although
difficult from a physics standpoint, may be
significantly superior to D-T from an
engineering/technology viewpoint. The economics
may be in question because of poorer reaction
cross-section. However, the environmental/
political influences and pressures that will

o   TANDEM D-T $\eta_{net} = .8\ (\eta_{th}) + .2\ \left[(\eta_{dc}) + (1 - \eta_{dc})\right]\eta_{th}$

   $\eta_{net} \approx .32 + 15 = 47\%$

---

o   TANDEM D-D $\eta_{net} = .5\ (\eta_{th}) + .5\ \left[(\eta_{dc}) + (1 - \eta_{dc})\right]\eta_{th}$

   $\eta_{net} \approx .20 + .38 = 58\%$

---

o   TOKAMAK D-T or D-D,

   the MTGR, or a

   SOLAR CONCENTRATOR.

   $\eta_{net} = \eta_{th} \approx 40\%$

Fig. 9   Net Efficiency potential of different energy sources.

inevitably be brought to bear on fusion's acceptability to the community cannot be ignored. The inexhaustible energy advantages of deuterium fuel over tritium fuel are also important. We consider the D-D cycle or other advanced cycles as a necessary backup for the D-T cycle. We recommend that the fusion community begin to seriously assess these cycles using today's physic's base and avoiding the pitfall that our perceptions ten years ago indicated that D-T was difficult enough and we didn't need another order of magnitude problem. Since then physics and engineering progress has moved us several orders of magnitude closer to success. In the meantime political and social pressures against "things nuclear" have increased an order of magnitude. We must always view fusion from all areas: technical, political, social, institutional, environmental so that as we grow larger in national importance we retain our advocates.